Analysis and Prediction Techniques

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Publication date:
1996

Document Version
Publisher's PDF, also known as Version of record

Link to publication from Aalborg University

Citation for published version (APA):
Heiselberg, P. (1996). *Analysis and Prediction Techniques*. Dept. of Building Technology and Structural Engineering. Indoor Environmental Technology Vol. R9656 No. 64

INSTITUTTET FOR BYGNINGSTEKNIK

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PAPER NO. 64

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ANALYSIS AND PREDICTION TECHNIQUES

DECEMBER 1996 ISSN 1395-7953 R9656

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Printed at Aalborg University

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Abstract

In large enclosures, common ventilation strategies, as complete mixing, require considerable amounts of energy to move and condition enormous amounts of air. The air flow pattern should therefore be well planned and controlled to ensure an acceptable indoor air quality in the occupied zone without the need for excessive air flow rates.

This part of the summary report concentrates on describing methods for designing and analysing ventilation in large enclosures. It includes application of different mathematical models in the design process for simulation of temperature distribution, air motion and contaminant spread in order to evaluate performance and locate problems.

At the first stages of the design process information is rather limited. Approximate HVAC solutions are developed based on engineering experience and use of appropriately simple analytical tools (macroscopic models) to save design work. At the latter stages of the design process more information is available and more detailed analytical tools (microscopic models) can be applied to evaluate the proposed air flow design.

The Annex 26 work has resulted in an easy and strategic procedure for designers and HVAC engineers to design ventilation and air conditioning by choosing adequate models at each design stage.

Key Words

Large Enclosures, Air Flow Modelling, Energy Efficient Ventilation.

Introduction

Large enclosures, for example concert halls, sports centre and ice rinks, office buildings, factory halls, atria, shopping centres or passenger terminal buildings often present unsolved problems related to energy and air flows such as unwanted thermal stratification, local overheating, draughts or uncontrolled contaminant spreading. Therefore, within the International Energy Agency - Energy Conservation in Buildings and Community System (IEA-ECB&CS) a joint research programme, Annex 26 "Energy-Efficient Ventilation of Large Enclosures was established to address these problems.

A large enclosure is defined as an enclosed ventilated air space at least partly occupied and containing various contaminant and heat sources. It is distinguished from other occupied rooms by the strong effect that buoyancy and temperature differences have on air motion, in particular on vertical streams of warm or cold air. Large enclosures may be complex and have partitions and openings.

In large enclosures common ventilation strategies, like complete mixing, require considerable amounts of energy to move and condition enormous amounts of air. The air flow pattern should therefore be well planned and controlled to ensure an acceptable indoor air quality in the occupied zone without the need for excessive air flow rates. This is obviously possible since, in large enclosures, the occupied zone is relatively small. In large enclosures some designs suffer both from over-sizing of equipment and from excessive energy requirements, which are usually caused by the lack of knowledge and guidance at the design stage.

The objectives of Annex 26 were to increase the understanding of the physics of air motion, thermal stratification, and contaminant spread in large enclosures, and to develop methods to minimise within large enclosures energy consumption in the provision of: 1) good indoor air quality and comfort, 2) the save removal of airborne contaminants and 3) the satisfactory distribution of fresh air.

Annex 26 concentrated on analysing the response of the air mass in large spaces to thermal and other inputs from the building and the environment, and it aimed at reducing energy consumption by ventilation. The air flow is particularly important. Firstly, it provides a mechanism for relatively large scale energy transfer processes and, secondly, it has a strong relevance to thermal comfort, removal of airborne contaminants and provision of fresh air at the breathing level, which are of prime importance to comfort and productivity of the occupants.

The Annex addressed problems that are related to the elements of the design procedure for a real building: 1) design, 2) construction, 3) commissioning and 4) troubleshooting. Methods to solve these problems were developed including both development of measuring techniques for field measurements in large enclosures, development of design and analysis methods for air flow and ventilation, and increment of the understanding of the air motion by measurements in a number of case studies.

This part of the summary report concentrates on describing methods for designing and analysing ventilation in large enclosures. It includes application of different mathematical models in the design process for simulation of thermal dynamics of building components, temperature distribution, air motion and contaminant spread in order to evaluate performance and locate problems. The developed measurement techniques and the application of both measurement and modelling techniques on specific case studies are reported in other parts.

Analysis and Prediction Techniques for Large Enclosures

Techniques for design and analysis of ventilation can be categorised in two main groups according to the level of modelling detail. The first group is macroscopic models, which are simplified models for a first estimate and design development, such as flow element models, engineering models and zonal models. The second group is microscopic models, which are detailed models for design evaluation and troubleshooting, such as computational fluid dynamics (CFD) and scale model experiments. Add to this the ventilation efficiency model, which is strictly a method to evaluate the ventilation performance based on the results of the macro- or microscopic models or measurements in the actual building.

The different stages involved in the design process of a large enclosure can be divided into initial design phase, building design phase, ventilation design phase, ventilation design evaluation and troubleshooting, construction phase and commissioning (Waters, 1996).

At the first stages of the design process, when the architectural form of the building and the quality of the indoor environment are roughly sketched, information is rather limited. Consequently only approximate HVAC solutions are developed based on engineering experience (such as data on existing similar buildings) and use of appropriately simple analytical tools (macroscopic models) to save design work. However, for critical or unconventional spaces suitable previous experience or engineering methods may not be available. In such cases more elaborate tools (microscopic models) may be used earlier in the design process, but only for a coarse analysis to qualitatively evaluate different design options.

At the latter stages of the design process, where the HVAC and the architectural design are more highly developed and more information is available, more detailed analytical tools (microscopic models) can be applied to evaluate whether the proposed air flow design will work as intended, or there are problems with local thermal discomfort, low IAQ, condensation etc. The performance of the ventilation system can be evaluated by a ventilation efficiency model. If the design criteria are not fulfilled the models can be used for further troubleshooting and design improvement. However, for conventionally sized enclosures such detailed analysis is rarely necessary, as ventilation techniques for such enclosures are well established and application of more simple analytical methods will often be sufficient.

Table 1 summarises function, capability, obtained information and necessary resources for each type of analysis and prediction technique. In the following sections each technique is described in more detail including date requirements, expectations to results and application advantages and disadvantages.

Table 1. Outline of analysis and prediction techniques for air flow in large enclosures.

	Macroscopic Model	**Microscopic Model**	**Ventilation Efficiency Model**
Design Stage	Initial and ventilation design phase	Ventilation design evaluation and troubleshooting	Ventilation design evaluation and troubleshooting
Purpose	Macroscopic analysis of air flow and temperature distribution at a few typical points	Microscopic analysis of air flow and temperature distribution in detail	Evaluation of efficiency of HVAC system
Available models	Flow Element model Engineering model Zonal model	CFD based on turbulence model Scale model experiment	Analysis by experiment Analysis based on results of CFD
Output	Mean temperature Vertical temperature distribution Heat load Air Flow Pattern Boundary conditions for CFD	Detailed distribution of air flow and temperature Study of problems to be solved in design phase	Distribution of ventilation efficiency index Mechanism of heat transfer and air flow in actual situation
Necessary equipment	Personal computer etc.	Super computer or EWS for CFD Scale model with devices for model experiment	Super computer or EWS for CFD Scale model with devices for model experiment
CPU time	Few minutes	10 - 100 hours a case for CFD	1 - 10 hours a case for CFD
Required time for application	About half a day pr. case to make input data	About 1 week pr. case to make input data for CFD 1 - 3 weeks pr. case for model experiment	About 1 day pr. case to make input data for CFD 1 - 3 weeks pr. case for model experiment

Flow Element Models

The flow process in ventilated rooms can be divided into different elements such as supply air jets, exhaust flows, thermal plumes, boundary layer flows, infiltration and gravity currents. These flow elements are isolated volumes where air movement is controlled by a restricted number of parameters, and is fairly independent of the general flow in the enclosure. Flow element models are very useful in situations where the air flow pattern in a room is dominated by a single flow element or by flow elements which are not interacting with each other.

These semi-empirical models are often based on comprehensive measurement work and experience, but are also often developed under simplified geometrical and physical conditions. Therefore, they give very good results in cases where the conditions are close to the experimental conditions, while it can be difficult to apply them and get good results in cases that differ.

The greatest assets of the models are the fact that they are relatively easy to use, they require only a few input parameters, they are not very time-consuming and they do not demand any investments of importance. To use the models in a particular case it is necessary to define the geometrical and physical conditions, to find the appropriate model, to estimate the input parameters and to calculate the results using a pocket calculator or a spreadsheet program. At the same time this is the greatest disadvantage of the models. Many of the models are only applicable under certain conditions, and together with the limited requirements to the input parameters, the results will not give very detailed information about the air flow conditions but only the level of a few key parameters of the flow.

Conventionally sized enclosures have often simple geometrical and physical conditions and the air flow pattern is often dominated by a single flow element or by flow elements which are not interacting with each other. Consequently an analysis of the air flow conditions by the flow element models will be sufficient in the design of the air distribution system.

Large enclosures have often very complicated geometrical shapes and physical conditions, and the air flow will often consist of several flow elements occurring at the same time. The flow elements will only dominate the air flow conditions in relatively small parts of the enclosure, and the flow path will often be influenced by other flow elements. In such cases the flow element models will only be useful at the first stages of the design process to keep design costs down and, eventually, to estimate the air flow conditions in specific areas of the enclosure. More detailed analytical tools (field models) will be necessary to estimate the air flow and temperature conditions in the enclosure as a whole. However, the results from the flow element models will still be very useful as input and comparison.

Engineering Models

Engineering models are macroscopic models ranging from very simple calculation methods to elaborate models describing very complex problems. They include in the Annex 26 work models for natural ventilation in buildings, zonal models and building thermal dynamic models.

Natural ventilation occurs due to pressure differences between the inside and the outside caused by thermal buoyancy and wind, and the general aspects are described by models derived from the Bernoulli equation. The pressure distribution over the building envelope estimated from geometry, wind characteristics and temperature differences between the inside and the outside combined with the air leakage characteristics determines the induced ventilation rates. The results are velocities and flow rates in the openings. The large enclosure is essentially treated as a single zone with temperature stratification. The uncertainties in the model are closely related to the input parameters such as wind pressure coefficients and air leakage characteristics.

The main principle of zonal models is to split the indoor air volume into several macro-volumes, to write the mass- and energy balances and to compute mean values for temperatures, pressures and concentrations for each macrovolume. The main problem in zonal models is to evaluate the air flows (and to a less extent the heat fluxes) between the macrovolumes. A zonal model with a large application field and a good accuracy has been established by using specific laws for flow elements in volumes where they occur, and by linking air mass flows between zones with a pressure difference in other zones. The advantages of the zonal model are that it covers the whole flow field, that it, in principle, is rather simple and that analysis of time dependent phenomena is possible. However, detailed distribution of parameters can not be predicted, and prediction accuracy becomes lower when the flow field is complicated.

Air flow in large enclosures strongly depends on boundary conditions at surfaces which limit the space such as temperatures and heat fluxes. To calculate these often time dependent parameters building thermal dynamic models are used. Commercially available programs are developed with the purpose of simulating building and system performance. Often the models do not include sufficiently detailed descriptions of enclosure geometry, solar radiation and coupled internal convection and radiation exchange to make the results directly usable in detailed flow field analysis. Various approaches have been used in the Annex 26 work to solve this problem.

Field Models

CFD programs are described as field models or microscopic models, as they predict velocity, temperature and other flow properties throughout a whole space with a high degree of resolution. Micro simulation is based on the conservation laws of mass, energy and momentum, collectively called the governing equations for fluid flow, and it uses far smaller cells than macromodels.

CFD simulation of the flow field in large enclosures presents many difficulties due to the large size of the enclosure and the complicated flow field. For a large space it is only possible to conduct simulations with large computational cells, which makes it difficult to model the turbulent flow field accurately and also causes various types of numerical errors. As a result of the large size of the space the air flow in the enclosure is predominantly thermally driven, and the enclosure has typically a high degree of thermal coupling with the external environment. Therefore, it is especially important to model accurately surface heat transfer processes such as natural/mixed convection, solar radiation, long wave thermal radiation, heat transfer through external walls and structural heat storage. The complicated flow field in a large enclosure can be characterised as an elliptic flow composed of separation, reattachment, circulation etc., as anisotropic and highly three-dimensional flow, as nonisothermal sometimes with pronounced thermal stratification and, typically, as a predominantly buoyancy driven flow. Accurate prediction of such a flow field is very difficult and, the popular κ-ε turbulence model sometimes fails to give reasonable results.

CFD is a large software system composed of a great many subsystems, and hence its use demands an insight into topics such as HVAC technology, computational mathematics, fluid dynamics and turbulence statistics. The successful application of CFD to HVAC design requires a high degree of specialised knowledge and sound engineering judgement based on experience and expertise.

Annex 26 has studied all the processes, involved in room air flow in large enclosures, and addressed the problems that arise in large enclosure applications of CFD. It has resulted in a general guidance and suggestions to overcome application difficulties, and to get appropriate results at reasonable costs.

Despite the many difficulties in the application of CFD to large enclosure flow field analysis it is the only method that makes a detailed analysis possible. Although basic research into applying CFD to room air flow problems started about 20-25 years ago, it is only within the last decade that CFD has become practical for real design applications. This advance had been impossible without the rapid evolution of computer technology, and further advance in computer hardware and software technology, combined with the decreasing cost of computing, will undoubtedly make CFD a more accessible and attractive design tool in the future.

Scale Model Experiment

The principles and methods of scale modelling in ventilation applications have a long tradition and are considered useful in ventilation design, especially, in air distribution in large enclosures. Scale model experiments are performed mostly to determine air flow patterns in the enclosure under certain boundary conditions determined by the indoor technology processes, the building construction and the outdoor climate. Air flow patterns are often visualised and temperatures and mean velocities are measured.

It is assumed that similarity of the air mean velocity fields can be fulfilled when the air flows in real objects and in scale models are fully turbulent. Similarity conditions include geometrical similarity, similarity of the physical process and similarity of boundary conditions. In modelling of air distribution processes under steady state conditions the following nondimensional numbers determine the similarity of velocity and temperature fields: Reynolds number ($Re = uL/\nu$), Archimedes number ($Ar = \beta g L \Delta T/u^2$) and Prandtls number ($Pr = \nu/a$).

In many cases it is impossible to maintain all determining similarity numbers equal simultaneously for the whole ventilation process range. Therefore according to the experimental target, it is valuable to find out, which part of the general process would be of special interest for modelling, and in which part physical simulation would be more suitable (e.g. substitute boundary conditions). In this way, using the partial modelling method, model construction and experiment can be much simplified. Equality of the nondimensional numbers Ar and Re can not be fulfilled at the same time in both a full-size ventilation system and a scale model, when air is used as model fluid. However, if self similarity of velocities and air flow patterns are assumed in turbulent flows, a physically reasonable simplification can be obtained, if the lowest level of the Reynolds number, above which the flow in the scale model becomes Reynolds number independent, is identified. In this way, using approximate modelling, it is sufficient to maintain identical Ar - and Pr numbers and Re numbers above a critical value.

Scale model experiments require a proper approach in model design and experimental organisation. In constructing the model it is crucial to choose model length scale so air flows within the self-similarity range of the Reynolds number are ensured, to choose proper simulation of boundary conditions, to choose temperature difference scale so relevant thermal boundary conditions and required accuracy of air velocity measurements can be maintained and to adjust the model so air flow pattern visualisation and field measurements of parameters can be carried out in a convenient way. The errors of the approximate modelling method will be smaller and the test results more reliable the closer model size and flow parameter values are related to those in the full scale object. It is advisable to divide the problems investigated into those which require precise quantitative analysis with the use of partial modelling methods and those for which qualitative observations in small models, but of the whole object, may be sufficient.

Ventilation Efficiency

Ventilation efficiency is constituted of a number of concepts that reflect various aspects of the ventilation performance during both stationary and transient conditions, and comprises the performance both locally and globally. These concepts are based on actual concentrations, temperatures etc. Therefore, there is not any particular ventilation efficiency model because any model, physical model or computational model, that provides information about the actual variables can be used to assess the ventilation performance. The reliability of the assessment of the ventilation performance is therefore totally dependent on the reliability of the model providing information about the state in the ventilated space.

The connection between energy efficiency and ventilation efficiency is that an efficient system with respect to e.g. contaminant control, requires a smaller air flow rate to meet the design conditions in the occupied space of the enclosure and, thereby, a reduced need of energy for the transport of air. An efficient system may also require a smaller plant than usually. With respect to temperature control an efficient system requires a smaller temperature difference between the supply and the conditions in the occupied space than a less efficient system and, subsequently, less energy is required to meet the specified requirements.

To create an efficient ventilation in large enclosures the fact that the occupied zone is much smaller than the total volume of the enclosure is used. Therefore, to create uniform conditions within the whole space by using mechanical ventilation will not be energy efficient. Instead one should strive to create non-uniform conditions and to use the non-occupied part of the building as a storage for heat and contaminant. If this can be done, depends on the possibility of "isolating" the occupied space from the remaining part of the building. In isolation of different parts from each other the properties of stratified flow can be used.

One general prerequisite of energy efficient ventilation is source control. This has not only implications for the plant size, but also because the smaller the load the easier efficient ventilation can be obtained. Source control of heat is particular important because there is always a transport of heat by exchange of radiation between surfaces that can "see" one another, which means that it is not possible to obstruct transfer of heat between different zones.

CONCLUSION

In large enclosures common ventilation strategies, like complete mixing, require considerable amounts of energy to move and condition enormous amounts of air. The air flow pattern should therefore be well planned and controlled to ensure an acceptable indoor air quality in the occupied zone without the need for excessive air flow rates.

This part of the summary report has summarised the use of various models for predictions and analysis of ventilation and indoor climate in large enclosures. The models provide various information, and the contents of the information given from the models as well as the degree of prediction accuracy of the models differ for each model. At the first stages of the design process information is rather limited and approximate HVAC solutions are developed based on engineering experience and use of appropriately simple analytical tools (macroscopic models) to save design work. At the latter stages of the design process more information is available and more detailed analytical tools (microscopic models) can be applied to evaluate the proposed air flow design.

The performance of these models is reviewed from this point of view and given in Table 2 together with comparisons of advantages and disadvantages. Table 2 gives the designers and the HVAC engineers an easy and strategic procedure for designing ventilation and air conditioning by choosing adequate models at each design stage.

Table 2. Performance comparison of various analysis and prediction techniques.

	Flow element model	Zonal model (Eng. model)	CFD	Scale model experiment	Ventilation efficiency
Outline of model	Each element of flow, i.e. jet, plume, boundary layer flow etc., is analysed individually Entire flow field is examined by combination of these flow elements	Entire space is divided into several zones Balances of air flow rate, heat flux etc. are analysed, thus zone mean values of velocity, temperature and concentration are given	Space is divided into small cells, total number is about 10^4 - 10^5 Discretized transport equations of velocity, temperature, concentration are solved with finite difference method	Indoor climate of large enclosures is measured using scale model of the space Similarity conditions between real space and model scale are important	Ventilation effectiveness for supplying fresh air and removing contaminants is analysed using results given from various models
Macro- or micromodel	Macromodel	Macromodel	Micromodel	Micromodel	–
Timedependent analysis	Difficult	Possible	Possible	Impossible	–
Limitation	Only the area of the flow element is analysed	Detailed distribution can not be predicted	A large number of cells are required for large enclosure analysis	Very difficult to satisfy similarity conditions accurately	Analysis dependent on results of other models
Input data requirements	Definition of type of flow element Empirical constants for supply jet, plumes etc. Temperatures of supply air, room air, surfaces Source heat flux	Zone division Boundary conditions at walls Location of heat sources etc. Properties of flow elements etc.	Mesh layout Boundary conditions for velocity heat flux etc.	Properties of supply jet etc. for calculation of similarity conditions Boundary conditions for interior heat sources and wall surface temperature etc.	Room air distribution Location of contaminant source Location of supply and volume flow rate of fresh air
Output information	Velocity and temperature distribution for each flow element	Mean temperature, pressure and concentration for each zone	Velocity and temperature distribution for each cell Wall surface temperature when radiation simulation is coupled	Space distribution of velocity and temperature Number of measuring points is limited due to experimental load	Ventilation efficiency evaluation Concentration distribution
Advantages	Practice is very simple and fast	Practice is rather simple Analysis of time-dependent phenomena possible	Very detailed analysis possible Presentation using CG techni-que is powerful	Measurement of physical phenomena is basically reliable	
Disadvantages	Can not be applied where flow elements interact with each other	Prediction accuracy becomes lower when flow field is complicated	Grid design and input data require large human work load Large CPU time is required	High experimental load (time, money, work)	

Acknowledgements

This summary report is based on a part of the related Annex 26 report (Heiselberg et al. 1996), edited by Prof. Murakami and with contributions from the following authors:

Dr. Dario Aiulfi, Switzerland
Mr. Hassan Bouia, France
Dr. Gian Vincenco Fracastoro, Italy
Dr. Per Heiselberg, Denmark
Dr. Kazuki Hibi, Japan
Dr. Christian Inard, France
Prof. Shinsuke Kato, Japan
Assoc. Prof. Yasushi Kondo, Japan
Dr. Hans Martin Mathisen, Norway
Prof. Stanislaw Mierzwinski, Poland
Prof. Shuzo Murakami, Japan
Dr. Shinichiro Nagano, Japan
Prof. Peter V. Nielsen, Denmark
Mr. Yoshiichi Ozeki, Japan
Ing. Marco Perino, Italy
Prof. Zbigniew Popiolek, Poland
Prof. Mats Sandberg, Sweden
Dr. Jacobus Van Der Maas, Switzerland
Mr. Shinji Yamamura, Japan
Mr. Mutsumi Yokoi, Japan

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